Transforming sound by Cordis-anima physical models

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TRANSFORMING SOUNDS BY CORDIS ANIMA PHYSICAL MODELS

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ABSTRACT

Since the early days of computer music, a variety of algorithms have been developed and dedicated to the processing of musical signals thus providing an important workbench for musicians. Although most of them were inspired from natural phenomena like the delay effect from the reflections on a cliff or the variant filtering (like the Wah-Wah) effect from the modification of the vocal tract when we pronounce different vowels, they were designed using techniques based on signal manipulation with mathematical operations as the domain of signal processing claims. This divergence from the physical phenomenon and the simulation algorithm may be a barrier for the conception of new effects and mostly for their efficient control. Based on this remark we where motivated to explore the simulation universe of CORDIS-ANIMA, a physical modelling language dedicated to reproductions of physical objects from the real world, for a research in the domain of digital audio effects. This article introduces some elementary mathematical operations and several classical signal processing models for filtering designed with the CORDIS-ANIMA formalism: a high pass filter, a band pass filter and a time variant band pass filter. Furthermore some general concepts concerning their control will be presented.

1. INTRODUCTION

Digital audio effects – as an acronym DAFX – are digital systems that modify audio signals [1]. These transformations are made according to some sound control parameters that the algorithm permits and deliver output sounds. The control in a wide sense signifies all the possible methods available to the user for accessing the various parameters of the system (GUIs, abstract algorithms, physical models, gestural interfaces, sound features). Since it is the only link between the user and the algorithm, it does not only play an essential role on the design of the digital effect but also constitutes a basic part of it. The user will therefore base his compositional perspectives on this control mechanism.

Many taxonomies for the digital audio effects were proposed [2]. Taking into account the context of our research, it would be possible to classify the DAFX in two main categories (mainly used to classify the sound synthesis techniques):

i) *The techniques based on Signal Processing.* The discrete-time system is described as an abstract mathematical operator that takes the input sound sequence and transforms it into another sequence.

ii) *The techniques based on Physical Modeling.* The discrete-time system is described as a digitally simulated physical system that takes the input sound sequence temporally described and transforms it into another sequence.

Physical Modeling is increasingly used and applied for musical purposes [3]. Generally it is proposed as a convincing and realistic synthesis of real acoustical instruments. Recently it has been demonstrated that the mass-interaction physical modeling scheme can be a general means for creating music instead of just sound synthesis [4], [5]. Thus a physical modeling approach will be introduced which uses the mass-interaction scheme from the CORDIS-ANIMA formalism [6] in order to transform and process sounds.

For this exploration over the modular space of CORDIS-ANIMA, the GENESIS [4] graphical environment was used which among all offers flexibility for the conception of the algorithms. In this point the aim was to design the digital audio effect system by "physical thinking" and not by "signal thinking". In other words for us the manipulated object was the physical quantity that carries the musical information (position or force for the CORDIS-ANIMA case) and not the mathematical abstraction made when the term signal is used which may describes any physical quantity. The "canvas" and, above all, the strategy followed for the conception of these effects was the Newtonian mechanics and the common experience from the physical world.

Therefore the purpose of this study is to offer a different approach to the design of digital audio effect systems including the algorithm that transforms the sound, the control and the representation of the complete system. CORDIS-ANIMA networks or sometimes the equivalent GENESIS representation were adopted for this research and not block diagrams commonly used for the representation of discrete time systems. This offers an immediate physical interpretation of the general procedure. However for the analysis other system representation were used like transfer functions, difference equations or state space equations.

This research was also a part of a broader work on the development of a large library of GENESIS models called *Instrumentarium* concerning sound synthesis, sound processing and sonic events generation. This work will demonstrate and explain the possibilities of the GENESIS compositional environment based on the idea of "Physical Thinking".

2. CORDIS-ANIMA AND GENESIS

CORDIS-ANIMA is a real-time mass-interaction physical modeling system. This highly modular language was used during this study for the conception and the simulation of physical models that play the role of digital audio effect units.. CORDIS-ANIMA allows designing and simulating virtual objects that are composed by two types of elements, called modules:

- <MAT modules represent punctual material elements. The most used is the MAS module, which simulates an ideal inertia.
- <LIA> modules represent physical interactions between pairs of <MAT> modules. Available interactions are based on linear or nonlinear elasticity and friction.> modules

Thus, CORDIS-ANIMA models are networks of interconnected <MAT> and <LIA> modules.

Position and force are the two fundamental variables upon which CORDIS-ANIMA modules operate. A <LIA> computes two opposite forces according to the relative distance and/or velocity of the two <MAT> it links. A <MAT> computes its position according to the forces it receives from the <LIA> modules it is linked with. It should be noticed that some <MAT> modules are fixed points, so received forces have no effect on them. The algorithms can be found on [6], [7].

GENESIS is a graphical environment for musical creation based on CORDIS-ANIMA. The user builds CORDIS-ANIMA networks at an elementary level, since models are created by direct graphical manipulation and connection of individual modules on a virtual workbench. A number of higher-level tools are available for editing multiple parameters at the same time, generating large structures, visualizing models during simulation, etc. GENESIS implements ten types of modules. While CORDIS-ANIMA does not specify the dimensionality of the modules, GENESIS' simulation space is one-dimensional. <MAT> modules can only move in the direction that is perpendicular to the workbench, and distances and velocities are computed along this axis. For convenience, graphical manipulations take place in the 2D-space of the workbench, but the position of the modules on this plane have absolutely no consequence on the simulation: the workbench representation is only topological.

The normal set of GENESIS' building blocks is composed of:

- Linear modules: ideal mass (MAS), fixed point (SOL), second-order damped oscillator (CEL), elasticity (RES), friction (FRO), elasticity and friction combined (REF);
- Nonlinear interactions: the BUT and the LNL;
- Output modules: the SOX and the SOF, which respectively record a position and a force signal.

The BUT module simulates a conditional viscoelastic interaction. When the difference between the positions of M_1 and M_2 is smaller than a given threshold S, the BUT simulates the effect of a null-length damped spring between M_1 and M_2; otherwise, the two modules are not linked.

The LNL module is a user-defined nonlinear viscoelastic interaction. The user chooses the points defining two curves and may interpolate them using linear interpolation, splines, hyperbolic interpolation. The first curve (LNLK) gives the force to be applied to the modules according to the difference of their positions (nonlinear elasticity). The second curve (LNLZ) gives the force according to the difference of their velocities (nonlinear friction).

All <MAT> modules have an initial position (X0). Mobile <MAT> modules also have an inertia parameter (M) and an initial velocity (V0). <LIA> modules have elasticity (K=k/Fs^2 – k measured in S.I, Fs the sampling rate) and/or friction (Z=z/Fs, z measured in S.I) parameters.

During this study, we used a particular version of GENESIS that includes two extra modules, ENX and ENF. These are input modules that read a input file and translate its data into a time-changing position (ENX) or force (ENF). The input file represents a 1D temporal signal, sampled at 44100 Hz. It may derive from the measurement of a real gesture, the recorded movement of a <MAT> module in a previous simulation, or from an audio file. Consequently, input modules can be used to input any audio signal into GENESIS' models.

ENX is a massless <MAT> module whose position corresponds at each moment to the last sample read in the input file. ENF is a <LIA> module that connects to a single <MAT>, to which it sends a force proportional to the input file data.

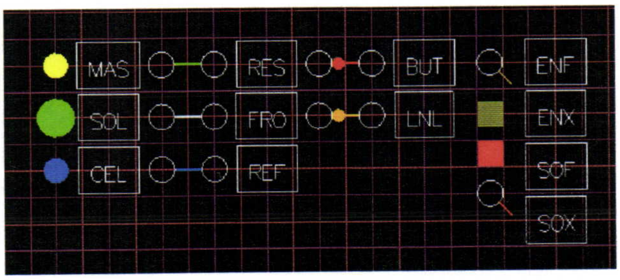

Figure 1 : *GENESIS basic modules*

3. GENERAL ASPECTS OF DESIGNING DIGITAL AUDIO EFFECTS WITH CORDIS-ANIMA

The basic idea behind the digital audio effects using physical modeling techniques is the forced oscillations. Several times, it happens that a system is set into vibration because it is linked with another oscillating system which is called the driving system. The important feature on forced oscillations is that the driven system does not feed back any appreciable amount of energy to the driving system so the perturbation effects are negligible. The input sound for the digital audio effects takes the role of the driving system.

In the simulation world of CORDIS-ANIMA there are two ways to connect two mechanical systems. It is possible to consider as the output of the first system and as the input of the second system either the force or the position, even though the variables in the Newtonian mechanics are duals and it's impossible to separate them. One the other hand the computer simulation and the real time control forces the separation of these variables. In general all physical communications (which are intrinsically non-oriented) are presented by two-way communication carried out by divisible input/output pairs (this is a constraint inherited by the information theory and the capabilities of the technology) [6]. A special case is envisaged for the force oscillations where the driving force or driving position is not presented by divisible input/output pairs but with a single input communication channel. Therefore we are able to apply directly a force to a <MAT> module or a position to a <LIA> module by a input file acting as the input sound (ENF and ENX modules in GENESIS – used only as external input). In a similar situation, whereas the physical model acts as the driving system, we can deliver a position using a <LIA> where it returns a zero force to the model or we can deliver a force using a <MAT> where it returns a zero position to the model (SOX and SOF modules in GENESIS – used only as external output). In this case the position or the force are considered as the output signal and it is recorded in sound files.

We can conclude that in the general case we can have as input-output the pairs force/force, force/ position, position / position, position / force (ENF/SOF, ENF/SOX, ENX/SOX, ENX/SOX modules in GENESIS). It is worth mentioning that we are able to use as input signal the force or the position of any CORDIS-ANIMA model designed for sound synthesis. For the last case much attention is required to control the –generally- undesired feed back link although it could give interesting results. Nevertheless in this article this possibility wont be explored.

In reality we always have feed-back links between interacting mechanical systems. However it is possible to arrive in situations of forced vibrations when we link mechanical systems where we approximately ignore the feed-back of energy either because the **linkage is very weak** or else because **the driving one has so much reserve energy** that the amount fed back is comparatively negligible [8]. So in CORDIS-ANIMA models, we can control the feed back interconnection following this principle and approximately pass from feed back interconnections to feed forward ones. We are able to do this either by changing the impedance of the systems (the one with the considerably higher impedance drives the other) or by using a weak link. We point out that in the digital audio effect case, when we connect two effect units, we use feed forward interconnections. It might be interesting for some combination of effects to conserve the feed back channel.

One very important aspect that we must not forget when we control the energetic scale of the phenomena is the undesired finite-word-length effects that are inherited in any digital realization of discrete-time systems. When we make computations with numbers of considerable different orders which is the case when two systems are in approximately in feed-forward interconnection these effects appear more. Moreover, it is worth mentioning that GENESIS is always normalizing the output. So even if we have a very weak signal it is still possible for it to be heard with the maximum amplitude; however if it is combined with other signals it may not be heard at all.

4. SIMPLE SIGNAL PROCESSING OPERATIONS

This paper presents in this section, the way that some elementary signal processing operations can be fulfilled by using the compositional blocks of CORDIS-ANIMA. For this purpose our ambition is to eliminate the feed-back link. As it has been already mentioned we are able to control the bi-directional energetic exchange between the interacting models. Special care has to be undertaken when using the above models with input sounds provided by other models dedicated to sound synthesis. It is clear that our aim is not to process the signals using mathematical operators implemented with these simulated mechanical structures but to present all the possibilities of the modeling language we use for signal processing. For some models we consider as input signal the force while for others the position.

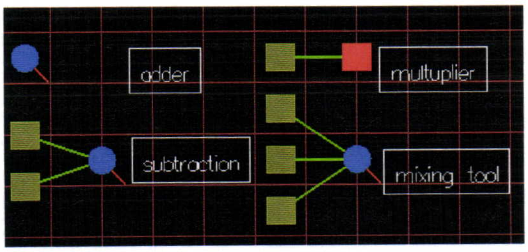

Figure 2 : *Models for simple signal processing operations*

4.1. Addition

When we apply a force to the CEL module we arrive in the situation of simple forced oscillations. Making the proper choice of parameters like $m = \frac{k}{F_s^2} = \frac{z}{F_s}$, we get an allpass frequency response. This can be verified directly by the CEL algorithm. So applying many input-forces to a CEL module we get an adder. The input/output relation is:

$$x = \frac{1}{mF_s^2} \sum F \tag{1}$$

We also notice an amplitude modification controlled by the inertia of the CEL module.

4.2. Amplification by a constant

The RES module can be viewed as an amplification system since the Input/Output equation is:

$$F_k = kx \tag{2}$$

Using it properly we are able to define accurately the amplitude of our input-position signal. It can be combined with an adder and other RES modules to give a mixing tool. We can avoid the disturbance resulting from the feedback channel by using low stiffness. For most cases a stiffness of a value 10^{10} times lower than the value of inertia will eliminate this undesirable effect.

4.3. Subtraction

A RES with a negative stiffness value inverts our input-position signal. When using it with the previous mixing model it gives as a result a subtraction. This resulting input/output equation is:

$$x = \frac{k}{mF_s^2} (x_1 - x_2). \tag{3}$$

5. FILTERING

At this point the essay will focus on some basic structures, which can be used for filtering purposes. As all linear systems can be viewed as filters, we can approach the linear CORDIS-ANIMA network by the same way. The linear CORDIS-ANIMA network where all the <LIA> elements are terminated by a <MAT> element results in a linear combination of second order IIR filters called resonators. The CEL module can be considered as a resonator. The number of filters derives from the number of <MAT> elements. Using modal analysis [8] we can verify that every input/output pair in a CORDIS-ANIMA network gives different linear combinations of those filters. We can control the resonating frequency of the filters by the stiffness and by the inertia. The damping factor has mostly impact on the bandwidth of the filters. Every network topology gives a different filter.

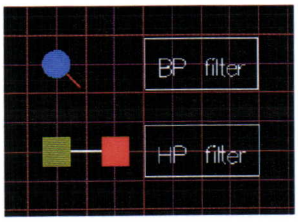

Figure 3 : *Models for band pass and high pass filtering*

5.1. Band pass filter

It is straightforward to verify by CORDIS-ANIMA algorithms that the CEL module has an input/output function

$$x(n)+[-2+\frac{k_{12}}{mF_s^2}+\frac{z_{12}}{mF_s}]x(n-1)+ \qquad (4)$$
$$[1-\frac{z_{12}}{mF_s}]x(n-2)=\frac{1}{mF_s^2}F(n-1)$$

We recognize that this transfer function describes a band pass filter realized by second order all-pole filter given in generally by the difference equation:

$$y(n)=b_0x(n)-a_1y(n-1)-a_2y(n-2) \qquad (5)$$

This filter is found in most computer music programs [9]. It is simple to compute the coefficients for a desired resonant frequency f_r and bandwidth BW approximately by the expression:

$$k=mF_s^2(a_1+a_2+1) \quad z=mF_s(1-a_2) \qquad (6)$$
$$a_1=-2e^{-\pi BW/F_s}\cos(2\pi f_r/F_s) \quad a_2=e^{-2\pi BW/F_s}$$

There is another possibility for forced oscillations studied analytically by Eric Incerti [9]. Instead of applying a force to the CEL module, we apply a position or in other words we move the springs attachment point. Incerti have studied the coefficients of this transfer function in order to obtain constant amplitude and constant bandwidth.

5.2. High pass filter

The FRO module can be consider as a high pass filter. From the CORDIS-ANIMA algorithms we get for the this component:

$$F(n)=zF_s(x(n)-x(n-1)) \qquad (7)$$

It is a high pass FIR filter. Its amplitude response in the frequency domain is

$$H(f)=2zF_s\sin(\pi\frac{f}{Fs}) \qquad (8)$$

The cutoff frequency is $F_s/4$

5.3. Complex filters

Using combinations of the above models more complicated filters can be created. For example we can design filter banks by using many CEL modules with different physical characteristics, processing the same signal in parallel and adding the outputs with the model mentioned above. Similar systems can easily be used to model the performance of complicated linear systems like the resonant boxes of musical instruments. It is simple to pass from the mass-resort paradigm to the modal synthesis approach. We can also combine those models in cascading form. However this structure imposes problems due to the finite-word-length arithmetic when we use the decoupling techniques mentioned before.

The most interesting case is when more complex structures as strings, membranes and spirals are used. These topologies have already been studied for sound synthesis [11]. We can adopt these attractive networks and further study the relation between the topology and the resulting linear combination of resonators after the modal analysis. We will see in the next section these topologies offer direct physical control.

5.4. Time varying filters

The objective is to design filters where some characteristics like the gain, the resonant frequency or the bandwidth are time-variant. We have access on these perceptual characteristics indirectly by modifying the set of parameters offered by CORDIS-ANIMA.

A band pass filter with time depended resonant frequency and bandwidth can be designed using a CEL module. The CEL module, which is a simulated mass-spring linear oscillator, according to our previous discussion is as second order IIR resonant filter. If we dynamically change the physical parameters K, Z and M we affect the frequency response of the filter. CORDIS-ANIMA doesn't let abstract dynamic modification of these parameters during the simulation for reasons concerning the energetic coherence of the physical phenomenon. However it's possible using nonlinear stiffness to arrive in situations where we preserve this coherence and obtain dynamical control. Some issues of dynamical control will be synoptically examined in the next section.

It is necessary to mention that the CORDIS-ANIMA models used in GENESIS environment are 1-D simulation space models [12]. Hence the pre-stressed tension applied on the extremities of the models doesn't affect the oscillation frequency as it could be supposed. The same happens when a constant force is applied to a mass-spring oscillator network. The last statement is not valid for the case of networks where the elastic forces are nonlinear. Consequently a constant force, which may be called a "bias" force, does influence the frequency response of the oscillator. This principle was used to design time variant filters with CORDIS-ANIMA.

The system illustrated on the figure 4 is actually a nonlinear CEL. The nonlinearity is defined by the Force/Position characteristic that is edited graphically in GENESIS. The slope of this curve gives the spring constant. The mass is attached on two stable points (SOL). These are located symmetrically on different levels from the equilibrium point of the mass where we apply the input-force signal. By changing the position of the stable points it is possible to affect the "bias" force. Due to the symmetrical topology, the equilibrium position of the mass doesn't change. The positions of the stable points control the "bias" force. If these points are chosen according to the criterion $F_{bias} >> F_{input}$, they exclusively determine the position or the "functional" point over the nonlinear characteristic Force/Position and consequently the spring constant. The curve must be designed carefully in order to consider it linear for the displacements occurred by the input-force for every "functional point". Otherwise the system will no longer be a linear oscillator and distortion will occurs.

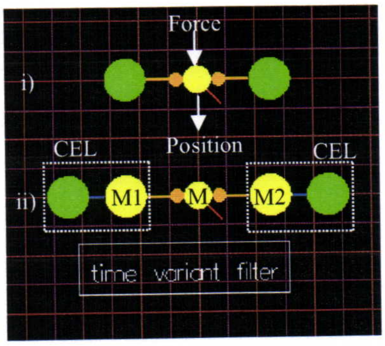

Figure 4 : *i)Non linear oscillator ii) Time variant band pass filter*

A Duffing oscillator has been chosen as a nonlinear oscillator with a restoring force of the form $F = \frac{k}{F_s^2} x(1 + \left(\frac{x}{d}\right)^2)$, where k is the spring constant for small displacements, and d is the characteristic displacement at which the linear and nonlinear contributions to the restoring force are the same [7]. The effective spring constant at the point x_0 is

$$k_e = 2\frac{k}{F_s^2}(1 + \left(\frac{x_0}{d}\right)^2) \tag{9}$$

This equation offers the possibility to choose the desired resonance when combined with the equation (6). The interesting situation is where the "bias" force is not constant (of course in this case we can no longer use the term "bias"). By means of changing the position of the fixed points dynamically we arrive in a two-pole time varying filter. One technique to achieve this is by using MAS modules in motion (M1 and M2 in figure 4). In this case the control problem appears which will be examined generally in the next session. In our example two CEL modules were used which provides a sinusoidal movement.

6. DISCUSSION : INTERACTION WITH THE MACRO-TEMPORAL SCALE

This section discusses the issue which is generally called *control* of digital audio effects. This term normally refers to situations where the communication between a control process and the effect unit is unidirectional. However, bidirectional communication is implemented in a number of digital audio effects, the most common being dynamic processors. Thus, *interaction* is a more general word to deal with the relationship between effects units and their "environment", especially in the context of mass-*interaction* physical modeling.

Issues related to this relationship are a part of what is sometimes called the *control problem* [13] (pp. 465). Indeed, sound synthesis and sound processing both need dynamical and complex control in order to reach the sound richness and expressiveness. Todoroff identified three means of interacting with digital audio effects, which are often mixed together: human-computer interfaces, audio feature extraction, and algorithms [1]. In all cases, the recurring question is the mapping between the control signals and the parameters of the effect unit. A common answer is to take into account high-level aspects of sound and music, i.e. to extract from the inputs (audio or gesture signals) descriptors related to perception, cognition, expressiveness, etc. For example, Verfaille developed a number of *adaptive effects* whose control stage takes as input both audio and gesture signals [2]. Feature extraction is performed on audio signals to provide control functions that are modified by gesture. Extracted perceptual features are diverse: perceived pitch and amplitude, roughness, sharpness, etc.

In the case of the interaction of the instrumentalist with his/her instrument, there is no mapping between gesture and sound since no representation is involved in this situation, but only physical processes.[1] This is also the case with CORDIS-ANIMA models (which reflects the fact that this formalism is intended as a tool for simulating the instrumental relationship). Indeed, sound synthesis structures, digital audio effects units and "control sources" are all of the same nature in CORDIS-ANIMA models, and their characteristics depends on the same set of variables (force, position, inertia, stiffness and viscosity). Consequently, there is no need to "translate" the output variables of a component into the input variables of another, but only to design appropriate physical interactions between them.

What we first called a "control source" is more generally a physical component that produces movements whose frequencies lie below the audition threshold. Such an object, which we call an *event generator*, is thus able to produce virtual gestures (e.g. a 1 Hz sinusoidal oscillation) or even slower movements. It works at the macro-temporal time scale, in contrast to the micro-temporal scale which corresponds to audio oscillations. As previously stated, the interaction between CORDIS-ANIMA objects may be unidirectional or bidirectional depending or their relative impedance. Thus, event generators may *control* a digital audio effect or *interact* with it. Event generators may be replaced by <MAT> modules controlled by a force-feedback device, which gives the user the ability to "play" the digital audio effect in real-time. This is not possible in GENESIS, which is a non real-time environment. For both cases the control/interaction is accomplished by *modification gestures* according to the taxonomy of instrumental gesture proposed by Cadoz [14].

A simple case of modification gesture applied to a digital audio effect has been introduced with the time varying filter: M1 and M2 oscillate at a slow rate, which produces a variation of the filter's center frequency. Instead of attaching M1 and M2 to fixed points, it is possible to link them to an event generator that will generate a more interesting evolution of the center frequency. Another example is the possibility to change the length of a linear string used as a

[1] On the other hand, we can state that the complex relation between the cognitive representation of musical ideas and the gestures needed to achieve them eventually becomes a form of mapping for an instrumentalist who masters his or her instrument. This is the result of a long learning process which involves multi-sensory perceptual loops.

complex filter. This results to a discrete change of the transfer function of the filter, since the vibrating modes of the string are modified (the number of its modes is equal to the number of DOF). For this purpose, we have designed a virtual finger that fixes a given MAS module for a chosen duration. Continuous transfer function change can be performed using a nonlinear string built with LNL modules similar to those presented in Section 5.4. Then, the virtual finger is used to elongate the string by pushing up or down one of its endpoints, which moves the function point of the characteristics.

In most cases, dynamically modifying the properties of a CORDIS-ANIMA digital audio effects is done by displacing some of its MAT modules (e.g. M1 and M2 for the time varying filter). Any event generator may be used for this purpose, provided that its impedance scale and the amplitude of its movements are adapted to the target effect unit. With CORDIS-ANIMA digital audio effects, the challenge is no longer to choose mapping strategies, but rather to find interesting event generators in a given musical context.

Our study focused on audio effects applied to sounds coming from the ENX and the ENF input modules. However CORDIS-ANIMA models are also able to generate sounds and furthermore to produce entire sound sequences [5]. CORDIS-ANIMA provides the unique opportunity to deal with music composition, sound synthesis and sound processing within a single environment and with the same concepts and tools. Thus, complex interactions between those three levels can be created. For example, it is possible to design models where exciter gestures and modification gestures are produced by the same virtual object. This would result in a strong correlation between musical structure and sound processing.

7. CONCLUSION AND FUTURE WORKS

This article described a research focused on the design of physical models that would transform and process sounds using the CORDIS-ANIMA formalism. Basically the idea was to explore for the first time systematically the capabilities of this physical modeling language using the GENESIS environment for the recreation of some classical digital audio effects.

An interesting point of this approach was that it allowed the conception of the transformation mechanism to be based on "physical thinking". It has been shown that it is possible to transfer the experience from the physical world for the conception and for the realisation of some digital audio effects like filtering and time variant filtering. This gives the opportunity to origin a research on sound processing using a "window" on mechanical physics offered by the formalism adopted.

It is needless to say that this attempt is limited to some categories of effect units. To give an example the design of physical models that emulate the transformations based on time segment processing is not possible and out of interest. Even if we achieve to memorize the input signal mechanically this changes our initial standpoint and our philosophy: The physical instrument level. Our principal ambition is to give to the effect units an instrumental "character" with the purpose of hopefully getting more "warm" or "live" sounds transformations, and setting up a relation between the system and the musician of the type instrument/instrumentalist. We hope as well that new DAFX algorithms will be derived by this physical modeling approach.

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